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Developing Design Principles for Game-related Design Thinking Activities

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Abstract
The aim of this paper is to identify emerging design principles when developing, piloting and implementing game-related Design Thinking activities for primary and lower secondary classrooms. The analyses are based on data from the large-scale intervention project GBL21 (Game-Based Learning in the 21st Century), which explores and measures how 1600 students working with game-related design activities in the subjects Danish, mathematics and science are able to develop design competencies such as being able to construct and communicate design solutions. In the paper, we focus on qualitative data from a pilot study on how two teachers adopt and enact one teaching unit in mathematics in grade 7. The challenge for the students is to design and construct a tangram game using the visual block-programming language Scratch with a set of agreed constraints (e.g. constructing pieces of a particular form). In our analysis, we identify design principles that support the enactment of the unit as exemplified by the two teachers. For our purpose, their teaching is interesting because they use quite different strategies when adopting the unit. One finding is that the material objects and close attention to dialogue are vital when coupling Design Thinking, game-like activities with subject matter (e.g. mathematics).

Keywords: Design-Based Research, mathematics, dialogue, Scratch, Design Thinking, game design

1. Introduction
In recent years, much emphasis has been put on the need for developing students' 21st Century Skills such as collaboration, creativity, communication and critical thinking in order to meet future demands of the students' personal lives, workplaces and society. In a Danish context, the need for innovative teaching methods, which can support the development of 21st century skills, has become quite clear following a large-scale empirical study of everyday teaching involving observations as well as analysis of student assignments and learning materials (Slot, Hansen & Bremholm 2016). The key findings show how teaching in school subjects such as Danish, mathematics and science predominantly involve teacher-driven instruction and students working with individual, text-oriented assignments, which only contribute to limited use of students' 21st Century Skills

One of the most promising approaches to developing students' 21st Century Skills is Design Thinking, which is a mindset and framework originally developed by professional designers in order to address and come up with possible design solutions to complex or "wicked" problems (Cross, 2011). This often involves talking to users about their needs and coming up fast with multiple design proposals, which are then tested through iterative processes. Design Thinking has spread to various domains and is currently being used by teachers in schools all over the world (Koh et al, 2015). However, the implementation of Design Thinking in schools is not without challenges. First, it may be difficult for teachers to organize and facilitate open-ended design processes, which are often different from their everyday teaching methods. Second, Design Thinking does not necessarily fit with existing timetables and curricular aims of the school subjects. Hence, there is a danger when using Design Thinking and other innovative methods in creating "islands of innovation" or exhibition projects, which tend to drown in teachers' everyday routines. Thus, it is important that Design Thinking activities are relevant and manageable by teachers in order to be integrated into everyday teaching.

Within the last decade, there has been an increasing interest in combining Design Thinking activities with various types of game elements for educational purposes. One example is the Quest-2-Learn (Q2L) school in NYC that has used a systems-oriented curriculum since 2006. Q2L-students are graded through *Experience Points*, asked to work on *Quests* instead of projects and offered cross-disciplinary subjects such as *CodeWorlds*, which fuses English and mathematics through systems thinking (Salen et al., 2011). Another example is the

FUSE Project, which turns the classroom into a game-infused studio environment by combining an online resource of STEAM activities with physical science experiments (Stevens et al., 2018). Its design principles involve students' interest-driven selection of challenges, collaboration with peers, failing and trying again as well as active teacher facilitation. Both projects involve a range of engaging and innovative ideas for mixing design activities with game elements in order to develop students' 21st century skills. However, they also challenge the structure and content of the existing school subjects.

In contrast to these two projects, GBL21 aims to integrate game-related Design Thinking activities within the curricular aims of existing school subjects. In the present paper, we wish to identify emerging design principles in relation to how teachers enact a specific GBL21 teaching unit. We are thus addressing the following research question: How to develop design principles for designing and enacting game-related design thinking activities? We explore the question by analysing a case from our pilot study of the GBL21 project. More specifically, we will describe the emergence of two design principles based on how two different teachers enacted the same teaching unit on game design in mathematics using the visual programming tool Scratch.

2. The GBL21 project

The GBL21 project is carried out as a RCT intervention at 19 schools from August 2019 through December 2020 involving 12 teaching units for both 5th and 7th grade with an additional 25 schools acting as control group. The teaching units all involve game-related design activities using a mix of analogue and digital game tools in order to address specific design challenges - e.g. how to design a board game in Danish in order to address issues with online toxic language, how to design sustainable energy production using a 3D simulation in science education, or how to design a digital tangram game in mathematics using the visual programming tool Scratch. The project aims to measure the positive effect of the intervention focusing on the students' academic and social self-efficacy, social and emotional well-being, perception of key curricular activities as well as the students' design competencies. In this way, we assume that by working with game-related design activities, the students are able to develop specific 21st Century Skills, which we here term design competencies. This involves students' abilities to emphasise with user needs and understand collaboration, to plan and prioritize design tasks, to generate new ideas, and to model design solutions using various types of representations. Moreover, the study also conducts observations and interviews at selected intervention schools focusing on teacher facilitation of the teaching units and student interaction across the different subjects. In order to develop the teaching units, GBL21 has carried out a number of pilot studies at selected schools including the present pilot on designing tangrams.

3. Generative design principles

It is well-documented in Design-based Research (DBR), implementation research, and studies on teachers' professional development that successful implementation of new teaching methods needs to strike a delicate balance between ensuring fidelity to the aims of the intervention and providing teachers with sufficient agency to adapt to their local school context and to investigate own ideas and expertise (Durlak & Du Pre, 2008; Røvik, 2016; Squire et al., 2003). Sometimes teacher adaptations are meaningful in relation to research goals, sometimes they are not.

In this paper, we aim to provide a local perspective on how teachers implement a GBL21 teaching unit. Following the methodology of DBR, GBL21 is founded on a series of *design principles*, which have guided the designs of the teaching units (Barab et. al, 2007). According to Baumgarter and Bell (2002), "design" refers to the "act of creating or modifying materials, activities, environments or other elements of practice in order to meet specific learning goals and function within a specific set of theoretical, pragmatic, and local constraints" (p. 3). They further argue that the aim of DBR is to articulate design principles, which "should inform design decisions that are made in the course of creating curricular material" (p. 5).

In GBL21, we have developed the following *generative design principles*, i.e. principles to support educational designers in designing the teaching units in accordance with the intervention:

1. Creating meaningful design challenges within the curricular contexts of Danish, mathematics, and science
2. Following the five phases of the design thinking process: explore, interpret, ideate, prototype, and test

3. Using analogue and digital game tools to frame and solve the design challenges
4. Documenting design processes through design logs and portfolios
5. Developing criteria for assessment and feedback relating to both disciplinary aims and specific design competencies

Our work with these generative principles has led to the development of a conceptual model, which can be used to understand the complex dynamics between various design principles. The model (see below) is inspired by prior work by Hanghøj (2017) on creating educational links between games and curricular aims.

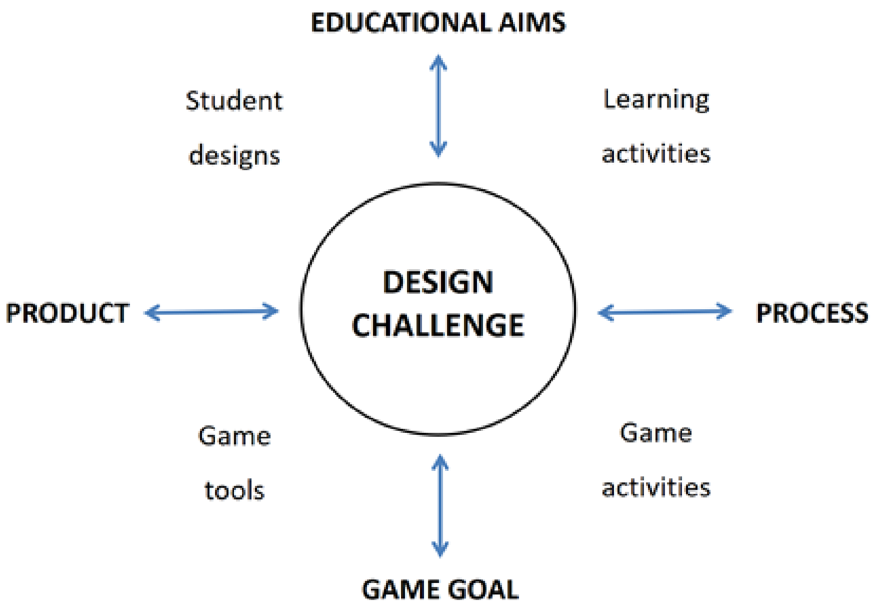

Figure 1: Conceptual model for developing the GBL21 teaching materials

The model highlights how each teaching unit is based on a core design challenge, shown in the centre of the model. This emphasises how the subject-specific design challenges intend to frame the different activities and aims of each teaching unit. Moreover, each unit involves a dynamic interplay between *educational aims* (both disciplinary aims and design competencies) and the *game goals* of the games played, developed and/or redesigned by the students. This relation between different types of framing is shown as a vertical dimension in the model. Finally, it is assumed that all units involve shifting foci between students' *processes* (i.e. the design activities of Design Thinking and the game activities involved in playing and testing games) and their use and design of *products* (i.e. the available game tools and the students' game designs). This relation is shown as a horizontal dimension in the model. In summary, the model illustrates how the design of the units tries to balance key dimensions and aspects, which all revolve around the core design challenge.

4. Design tangram puzzle games in mathematics

We will now use the model to describe the teaching unit in the pilot study, see figure 2. The design challenge of this unit is that groups of 7th grade students must design and construct (with the visual programming tool Scratch) a tangram puzzle game, which their classmates will find challenging to solve. In order to establish a balance between the tangram being neither too easy nor too challenging to solve or to construct, each group and the teacher agree upon specific criteria that their tangram should satisfy, for instance to include a piece formed as a regular polygon with 8 sides (see below). In order to solve this design challenge, students must be able to use mathematical competencies for problem-solving, learn basic programming skills and explore relationships between involved mathematical concepts (e.g. geometrical shapes and variables) and how to interpret and programme these with Scratch. Moreover, the students must also be able to use various design competencies such as being able to emphasize with other players, generate design ideas, plan their design activities, and, most importantly, to construct different prototypes (e.g. in carton and digitally) to be tested by themselves and classmates.

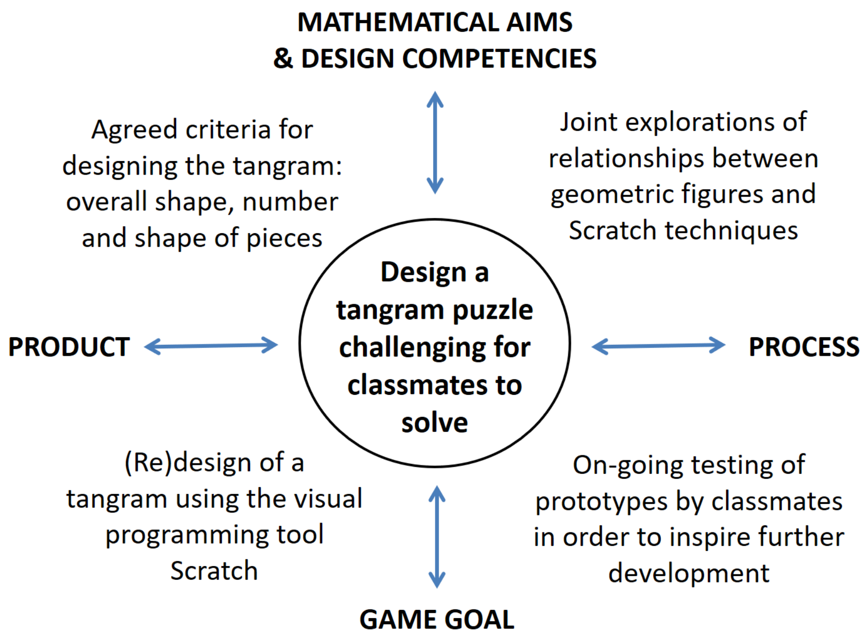

Figure 2: Description of the GBL21 teaching unit on designing tangram puzzle games

5. Material-dialogical spaces

Our on-going work with developing and refining design principles is informed by a material-dialogic perspective on how teachers adapt and enact the GBL21 teaching units. A dialogic pedagogy where teacher and students think aloud together to create new meanings, knowledge and understanding, has been emphasized in decades of research, e.g. in the context of working with new technology in the classroom (Mercer, Hennessy & Warwick, 2017; Wegerif, 2011). Referring back to Bakhtin, dialogue is *more* than just interaction. Not all interactions, where both teacher and students are talking, are dialogic. *Dialogic discourse* requires recognition of multiple voices and perspectives on the content worked on, whereas *authoritative discourse* focuses on one specific point of view. Furthermore, recent research extends the focus from verbal dialogue to a so-called material-dialogic approach taking specifically into account students' interaction with physical objects and the material world (Cook et al., 2019; Hetherington & Wegerif, 2018). Wegerif (2011) refers to a dialogic space as the dynamics of continuous emergence of meaning in a dialogue, "when students are listening to each other, asking each other for help and changing their minds as a result of seeing the problems as if through the eyes of the others" (p.180).

Following Wegerif (2011), it is important to analyse teachers' scaffolding of interactions in the classroom, including opening, closing, widening and deepening of dialogic spaces. Based on the new development in the field highlighting that voices engaged in dialogue are not only human, it is also important to recognize the crucial role of the other-than-human material objects when students are creating meaning and understanding through dialogue (Hetherington & Wegerif, 2018). In relation to this, Cook et al. (2019) refer to *passive* versus *active* use of material objects. Hence, the focus in the analyses in the present paper is not only on interaction, but also on *intra-action* with material objects, looking for *material*-dialogical spaces.

5.1. Macro and micro scaffolding

Our analytical focus is on teachers' enactment of game-related design thinking activities in the classroom. This analytical approach includes looking into the teacher's *scaffolding* of the activities and the opening, closing, widening and deepening of material dialogical spaces. Teacher scaffolding of the GBL activities might take the form as both macro- and micro-scaffolding (Prediger & Pöhler, 2015; Pollias, 2016). *Macro-scaffolding* is the planned sequencing of activities, including e.g. the planning of how to use various tools and material objects. *Micro-scaffolding* is the strategies the teacher uses at the spot, e.g. in dialogues, engaging student perspectives and asking questions (Pollias, 2016). In the present analyses the focus on teacher scaffolding is extended to include also how the 'voices' of materials might be enrolled.

6. Pilot study

6.1. The context of the study

Two teachers at the same school in the area of Copenhagen volunteered to participate in our pilot study consisting in teaching the 15 lessons that make up the mathematics unit on design of a tangram puzzle game. Both teachers – and their grade 7 classes – were unexperienced with using Scratch; the pilot being their first time at all using a programming tool in mathematic classrooms. The male teacher, P, has more than 30 years of teaching experiences, while the female teacher, A, graduated from teacher college one year ago having one year of teaching experiences. Teacher P spent spare time on learning some of the first programming languages, when computers first appeared, while A had no prior experiences with programming languages. Furthermore, none of the teachers had experiences with design thinking or using games systematically in the teaching of mathematics.

6.2. Collection of data

The main data for this qualitative multiple case study (Cohen, Manion, & Morrison, 2011) are:

- Classroom observations: field notes and video recordings of 10 lessons in each class,
- Memo writings by one of the authors immediately after each observation focusing on the teacher's actions in relation to Scratch and the students' work with the tool in relation to the mathematical content,
- A final focus-group interview with the two teachers focusing on their experiences with and recommendations to improve the teaching unit.

In the present paper, we are particularly interested in episodes, where the two teachers adapted and enacted the teaching unit differently. Consulting our field notes and memo writings, we selected a lesson in the beginning of the unit, where the students for the first time are to explore and develop Scratch scripts specifically in relation to geometrical figures. We (i.e. all the authors) made a preliminary analysis of the two corresponding videos extracts and selected specific episodes for transcription and further analyses.

In order to give an overview of the selected lesson, we describe shortly its tasks and their sequence. The first task presents a pre-programmed Scratch script that draws a sort of a rectangle with four right angles, but all sides of different lengths. The students are to discuss, what the script does, and how to change it in order to draw a proper rectangle. The second task is to optimise the script in terms of using a minimum of variables to construct first a rectangle and then a square. The third tasks presents a new pre-programmed script that uses the variable *The number of sides* and draws a square, when the variable is 4. Again the students are to discuss the structure, commands and parameters of the script, and then in task four to make new scripts that can draw regular polygons (i.e. polygons with equal angles and equal side lengths) of 3 sides (and then with 4 (i.e. a square), 5, 6, 7, … sides). This last task requires that the students know the sum of the angles in the regular polygon in question.

6.3. Analytical approach

We conduct two analyses of the case-teachers' adaption and enactment of the lesson focusing on how each teacher scaffolds the students' activities with the material objects (i.e. Scratch) by using the material-dialogic approach. First, we focus on the teachers' scaffolding at the macro-level by analysing the classroom's activity structure, the teacher's discursive interactions with the students and her/his intra-actions with material objects, looking for material-dialogical spaces. As a starting point for our analysis, we depicted each teacher's interactions and intra-actions on a timescale during the lesson (see figure 3). The purpose of the first analysis is to highlight differences in the two teachers' scaffolding of students' activities with the material objects and point out potentials (or no potentials) for creating material-dialogic spaces. Second, we analyse the teachers' scaffolding at the micro-level focusing on the strategies they use on the spot. We present one critical episode from teacher A´s classroom, that prove critical for creating material-dialogic spaces and for the students' learning opportunities. The purpose of the second analysis is to propose design principles that can guide teachers' social interactions with students when using games to engage students in design thinking activities in mathematics classrooms.

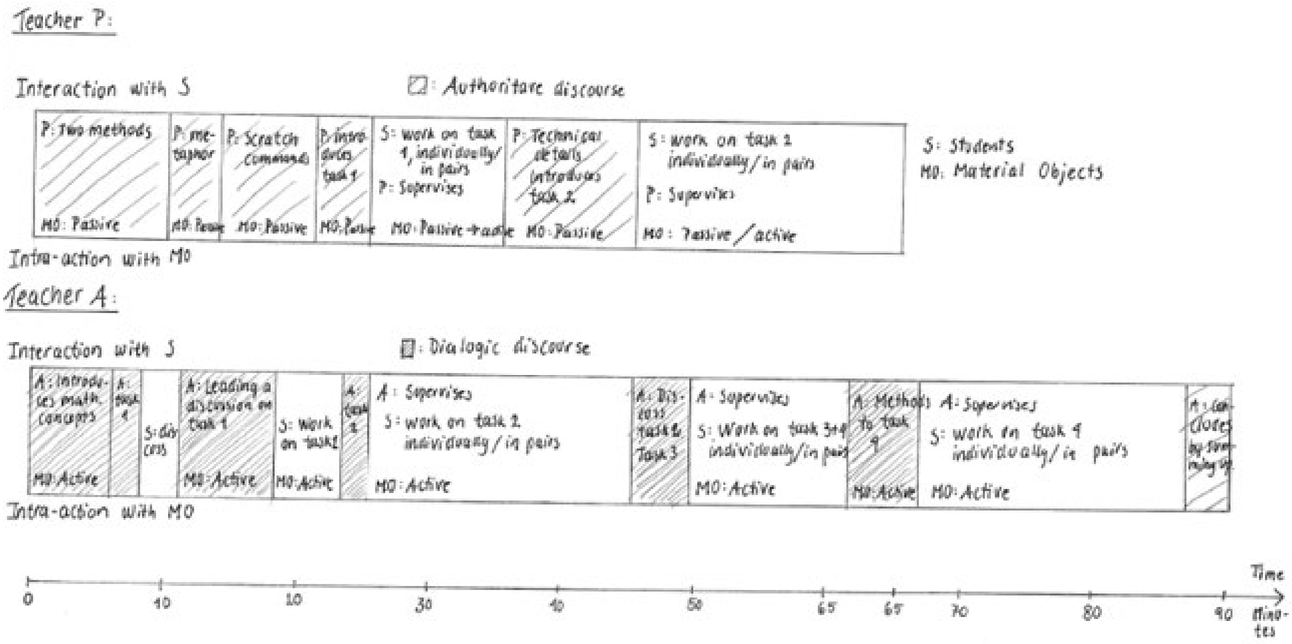

Figure 3: The overall activity structure in the two classrooms of teacher P and A.

6.4. Results and analysis of the teachers' scaffolding at the macro-level

Figure 3 shows that teacher A uses the overall organisation and activity structure of the lesson as suggested by the unit guide, while teacher P does not. Initially, P talks for a long time (25 minutes) in an authoritative way only asking students to answer relatively closed questions. Doing so, he focuses on three specific viewpoints: illustrating two mathematical methods to determine the angel sum required in task 4, providing a metaphor to understand programming and detailing Scratch-techniques. This indicates that one of P's scaffolding strategies at the macro-level is to provide students a priori the necessary knowledge (i.e. the methods and the Scratch-techniques) to work with tasks, before introducing these.

When introducing the first task, teacher P focuses on what the students should do (e.g. "You have to do this sequence of commandos on your computer"). Consequently, the students type mechanically the commands, mostly individually, without reflecting on how the commands function. Most students finish the task rather quickly, without knowing what to do then. After 20 minutes, teacher P shows the whole class this own solution and goes over some technical details which he had encountered himself or considered would be good for the students to know. Only then, does he ask the students about their work, but without following up on their contributions. Again, he introduces the second task by telling the students what to do. In the rest of the lesson, the students work on this second task.

Generally, teacher P's interacts with students in whole class sessions in an authoritative way focusing on specific points of view and occasionally allowing them to answer closed questions. On no occasions does he invite students to propose new ideas or pose an open question in order to explore different points of view or ideas. This also applies in relation to his own and the students' use of material objects. Teacher P intra-acts passively with these objects. First, he uses the objects for illustrative purposes (i.e. to demonstrate features of Scratch). Second, he presents and uses Scratch as a product, telling the students which commands to use and picking out programming issues that he considers relevant for them based on his own programming experiences. Third, his predominant focus on products also apply to the mathematics, as he presents and explains methods and concepts in whole class sessions that he assumes to be necessary for the students' later work with tasks. In doing so, teacher P closes down the students' opportunities to engage in genuine explorations of the mathematics in relation to Scratch, and to discover different ways to approach and solve the tasks. Hence, in this lesson teacher P does not establish a material-dialogical space where different perspectives are allowed and valued. Rather, he narrows the space for the dialogical interactions with the students in relation to the material objects and focuses predominantly on the objects and the content as products to be learned.

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In comparison, A starts by encouraging the students to explain the key mathematical concepts in the lesson and provides a drawing on the board for them to use in their explanations. During the lesson, teacher A repeats a cyclic pattern four times where she first introduces the (next) task in an explorative way (e.g. "What do you think happens in this script?") inviting students to find out for themselves and provides them time to do so. Second, she helps students work with the task encouraging them to try out their own ideas, and third and finally, she leads classroom discussions based on their work with the task, inviting them to contribute their different viewpoints and sometimes asking specific students to share their contributions. Teacher A intra-acts actively with the material objects, using them as active tools and mediums to engage students in inquiry-based processes for instance through hands-on exploration of Scratch programming in relation to constructing specific geometrical figures. In contrast to teacher P's enactment of the lesson, teacher A's students are able to make it to task 4 in the same time span and moreover they request a method to calculate the angle-sum, which teacher A interacts dialogically to establish with them. This shows that it is possible to engage students in learning processes and inquiry-based activities within comparable time periods, which in this case provide more meaning to students in relation to mathematics and material objects.

We conclude that teacher A creates a material-dialogic space where the students engage in explorative work by her way of scaffolding at a macro-level. In this space, the material objects function as active tools, which she asks early and consistently the students to use to explore, explain, construct, interact with and talk about in relation to geometrical constructions. Furthermore, she draws on a range of material objects such as pencil and paper, the black board, Scratch, and her own physical movements in order to engage the students in different processes. This material-dialogic space offers on the macro-level the students a number of learning opportunities, which is evidenced by the students' making of scripts that construct regular polygons with 5 sides and more (task 4). In comparison, teacher P's ways of macro-level scaffolding do not create a material-dialogic space that offers the same learning opportunities for the students.

On this basis, we propose the following design principle as important for teachers' scaffolding of students' work with material objects – especially programming tools – in relation to mathematics at the macro-level:

- To engage students early in working with the material objects through explorative processes such as not-trivial, subject-related constructions.

6.5. Results and analysis of the teachers' scaffolding at the micro-level

When talking about the second pre-programmed Scratch script, this unexpected exchange between teacher A and a student (S) occurs:

A: What are the variables in this script?
S: The colour of the pen. You can change it.
A: Yeees [hesitant]
S: The size of the pen?
A: Yeees [hesitant]
S: The number of turning degrees and the lengths of the sides. You can actually change everything.
A: Yes, but it is in particular the length of the sides.

By providing an alternative perspective on the understanding of a Scratch variable, a dialogical gap emerges in the episode. Teacher A reacts hesitantly to the student's suggestions, except the last one, which she emphasises, but by doing so she closes the dialog. An exploration of the student's perspective could possibly have widening and deepening the material-dialogical space and promoted a discussion of what constitute a variable in this new material-context and how this understanding relates to the mathematical concept of a variable. Our interpretation is, that teacher A is so challenged by her lack of experience with Scratch and of insights into the conceptual issues and misunderstandings it may entail for students, that she is unable to follow up on the student's unexpected contribution on the spot.

The episode is critical in the sense that it reduces the students' learning opportunities in the moment. Thus, it points out a new need of micro-level scaffolding when using material objects such as programming tools to relate its concepts/techniques to the concepts/methods of mathematics. On this basis, we suggest the following design principle at the micro-level:

- To scaffold classroom interactions in order to enhance constructive dialogues as regards both the subject matter, the material objects and not the least their interrelationships.

7. Discussion

It may well be argued that our analysis of two teachers teaching practices and the resulting two design principles are based on limited empirical data. Nevertheless, our findings resonate well with the current surge of interest in research on discovering the role of materiality in educational settings and, in particular, the complex interplay of dialogue and materiality (Cook et. al, 2019).

Our findings demonstrate the need for providing domain-specific guidance to teachers when conducting design interventions with new teaching methods, which resonate with their previous experiences as well as giving them support for enacting new types of material objects. Based on a large-scale study, Hetherington and Wegerif (2018) conclude that teachers often fail to create dialogical explicit links to the material objects they deploy. Neither do the two case-teachers A and P; at least not consequently throughout the lesson. We have, however, in the two cases both seen examples of a teacher succeeding in creating a material-dialogic space stimulating students' explorative work, and an example of what might oppositely be seen as missed opportunities for doing so. By focusing on material-dialogical spaces and dialogical gaps, GBL21 aims not only to develop generative design principles for supporting game-related design activities, but also to develop context-sensitive descriptions of how teachers will adapt and enact its 24 teaching units. Hopefully, this will creative a productive meeting between the generative design principles embedded in the teaching units and the local findings, which will be guided more by teacher and student perspectives.

Our findings illustrate how the two teachers A and P adapted the same GBL21 teaching unit, but in *very* different ways. As emphasised in implementation research (e.g. Durlak & Du Pre, 2008) adaptation to a specific class context may be decisive in creating positive outcomes, but fidelity to the aims and key ideas in an intervention is of course likewise important. Based on Durlak & Du Pre's findings as well as our own results, it is of crucial importance to identify and share with teachers what we see as "key ingredients", which absolutely need to be included and addressed in the GBL21 intervention. Our two identified design principles can be a starting point for this continuing work in the project, and inspire learning activities for teachers including their bottom-up input to inspire each other in adapting the units. We hope that our findings can also inspire beyond the project as the materiality of the (game) design tools affect the interpretation and enactment of mathematical concepts in a classroom setting, which may have implications both for mathematics education, and for the fields of game-based learning and design thinking.

8. Conclusion

We have with reference to two teachers' implementation of a GBL21 teaching unit in their 7th grade mathematics classrooms identified both challenges and possibilities. A main conclusion is that the use of material objects and teachers' scaffolding and close attention to dialogue are vital elements when coupling Design Thinking, game-like activities with subject matter content. This is formulated in the two design-principles: 1) At the macro-level, we recommend to engage students early in working with the material objects through explorative processes such as not-trivial, subject-related constructions. 2) At the micro-level, we emphasise the scaffolding of classroom interactions in order to enhance constructive dialogues as regards both the subject matter, the material objects and not the least their interrelationships.

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